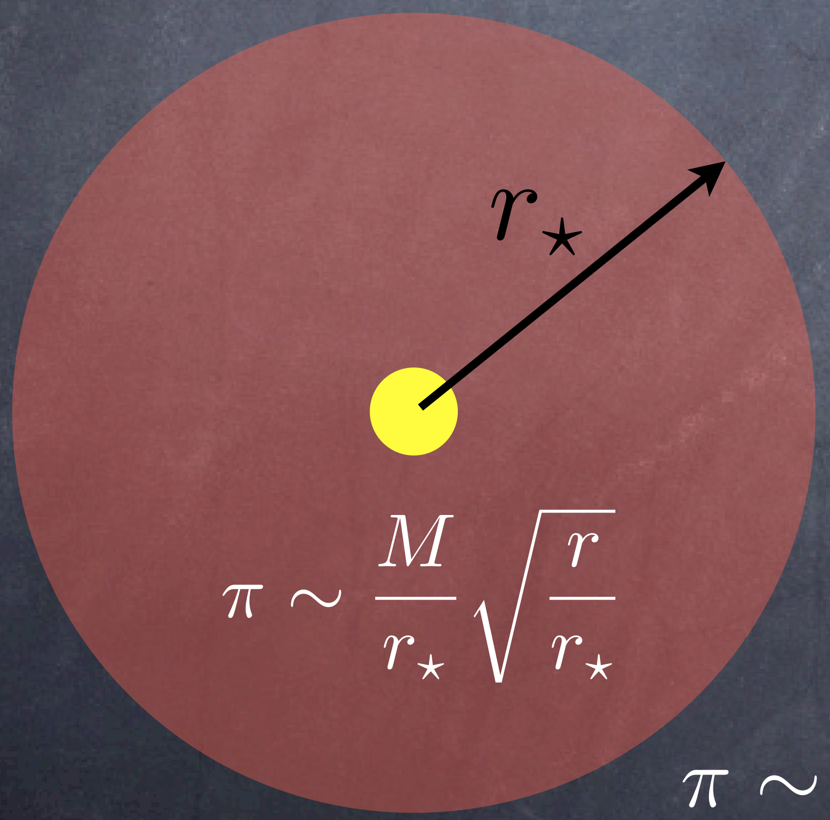
Galileon Mechanism

Vainshtein (1972); Arkani-Hamed, Georgi, Schwartz (2003)
Deffayet, Dvali, Gabadadze & Vainshtein (2002);
Luty, Porrati & Rattazzi (2003); Nicolis & Rattazzi (2004)

4d effective theory in DGP: $\mathcal{L}_\pi = 3(\partial\pi)^2\left(1+\frac{\nabla^2\pi}{3\Lambda^3}\right)+\frac{\pi}{M_{\rm Pl}}\rho$

which enjoys Galilean symmetry: $\partial_\mu\pi \to \partial_\mu\pi + c_\mu$

$$\boxed{3\nabla^2\pi + \frac{1}{\Lambda^3}\left[(\nabla^2\pi)^2 - (\partial_\mu\partial_\nu\pi)^2\right] = \frac{\rho}{2M_{\rm Pl}}}$$



$\pi \sim \frac{M}{r}$

where $r_\star = \Lambda^{-1}\left(\frac{M}{M_{\rm Pl}}\right)^{1/3}$

Field generated on a background below Vainshtein radius of large object: $\pi = \pi_0 + \varphi\,, \qquad T = T_0 + \delta T$

$$\mathcal{L} = -3(\partial\varphi)^2 + \boxed{\frac{2}{\Lambda^3}\left(\partial_\mu\partial_\nu\pi_0 - \eta_{\mu\nu}\Box\pi_0\right)}\,\partial^\mu\varphi\partial^\nu\varphi - \frac{1}{\Lambda^3}(\partial\varphi)^2\Box\varphi + \frac{1}{M_{\rm Pl}}\varphi\,\delta T$$

$$\sim \left(\frac{r_\star}{r}\right)^{3/2} \gg 1$$

Kinetic term is enhanced, which means that, after canonical normalization, coupling to δT is suppressed. The non-linear coupling scale is also raised.

Generalizations:

- Higher-order interactions
  Nicolis, Rattazzi and Trincherini (2009)
- Multi-galileons
  Padilla et al. (2010), Hinterbichler, Trodden and Wesley (2010)

Symmetron Mechanism

K. Hinterbichler and J. Khoury, Phys. Rev. Lett. (2010)

Instead of $m(\rho)$, here it is the coupling to matter that depends on density.

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + \frac{\phi^2}{2M^2} T^\mu_\mu$$

where T^μ_μ is stress tensor of all matter (Baryonic and Dark)

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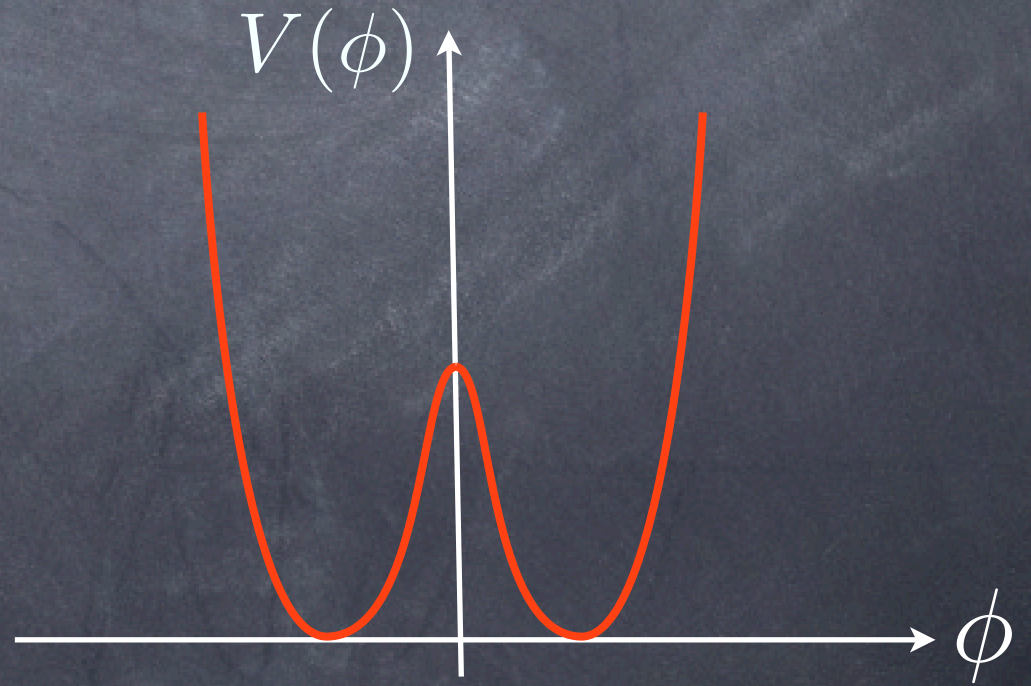
Potential is of the spontaneous-symmetry-breaking form:

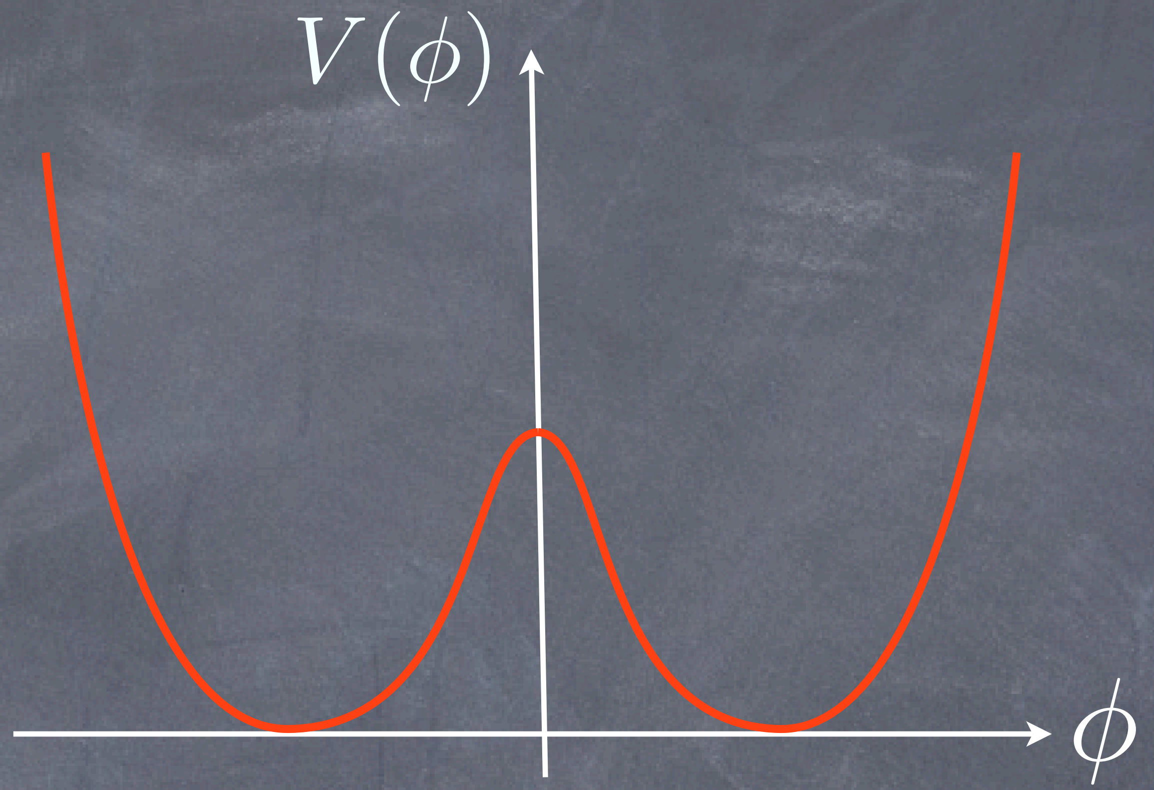
$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$



Most general renormalizable potential with $\phi \longrightarrow -\phi$ symmetry.

Effective Potential

$$\boxed{V_{\text{eff}}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4}$$



$\therefore$ Whether symmetry is broken or not depends on local density

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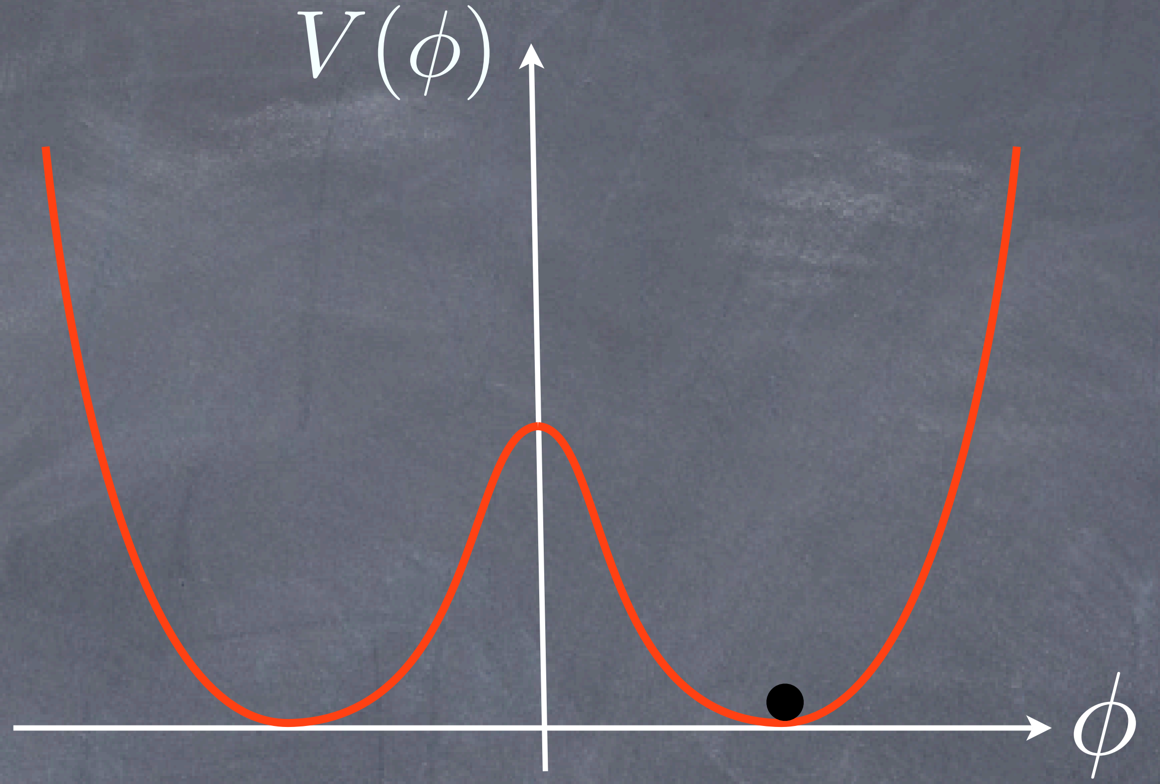

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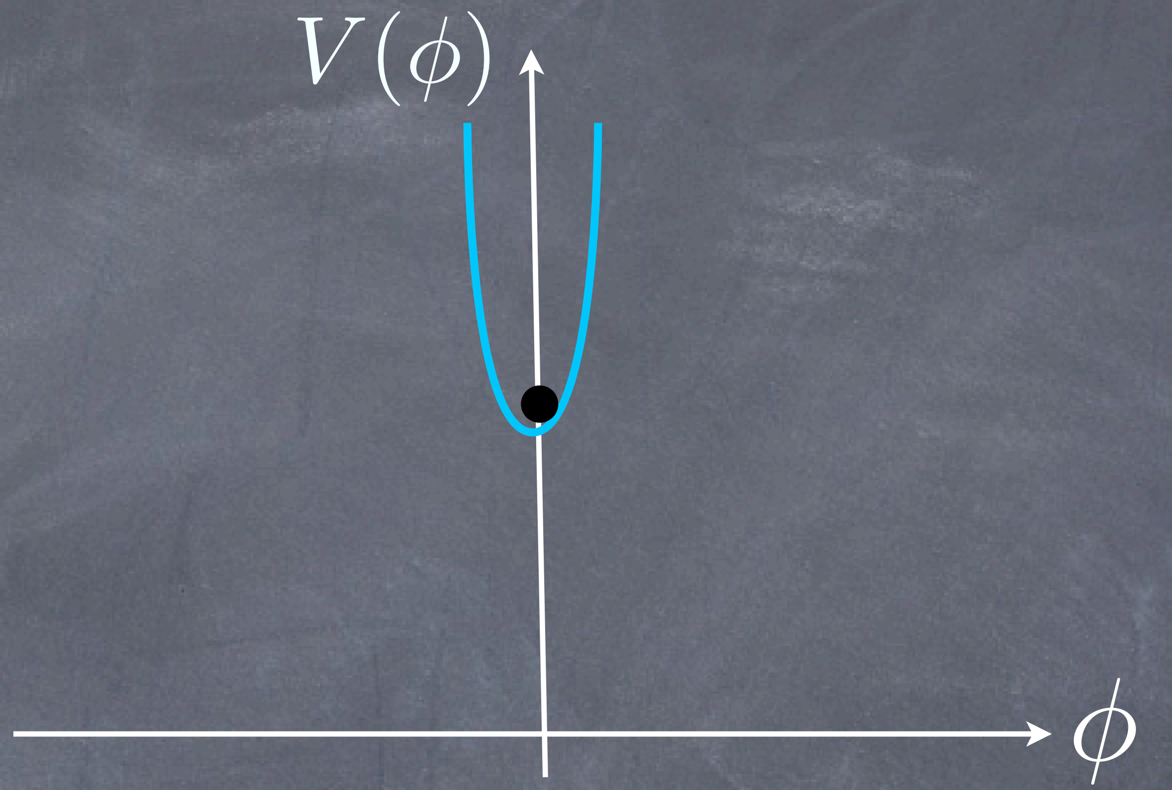
- Outside source, $\rho = 0$, symmetron acquires VEV and symmetry is spontaneously broken.

Effective Potential



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$\therefore$ Whether symmetry is broken or not depends on local density

- Outside source, $\rho = 0$, symmetron acquires VEV and symmetry is spontaneously broken.
- Inside source, provided $\rho > \mu^2 M^2$, the symmetry is restored.

Effective Coupling

Perturbations $\delta\phi$ around local background value couple as:

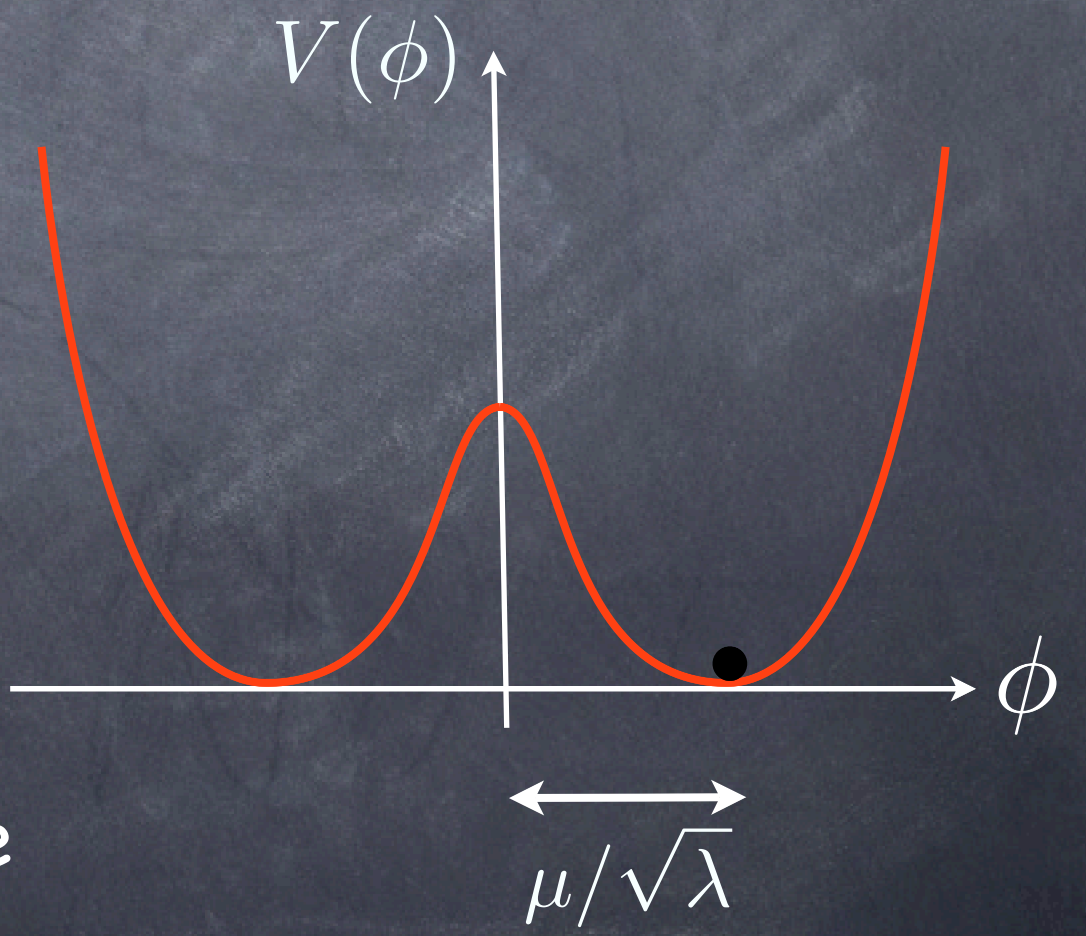
$$\mathcal{L}_{\rm coupling} \sim \frac{\bar{\phi}}{M^2}\delta\phi\,\rho$$

- Symmetron fluctns decouple in high-density regions
- In voids, where Z_2 symmetry is broken,

$$\mathcal{L}_{\rm coupling} \sim \frac{\mu}{\sqrt{\lambda}M^2}\delta\phi\,\rho$$

$$\sim \frac{\delta\phi}{M_{\rm Pl}}\rho$$

gravitational strength



$\therefore$ Gravitational-strength, Mpc-range 5th force in voids.

Inspiration...

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Symmetron Couch ($9500.00)

"NASA-style gravity reduction."

"Offers a unique multi-phase wave experience."

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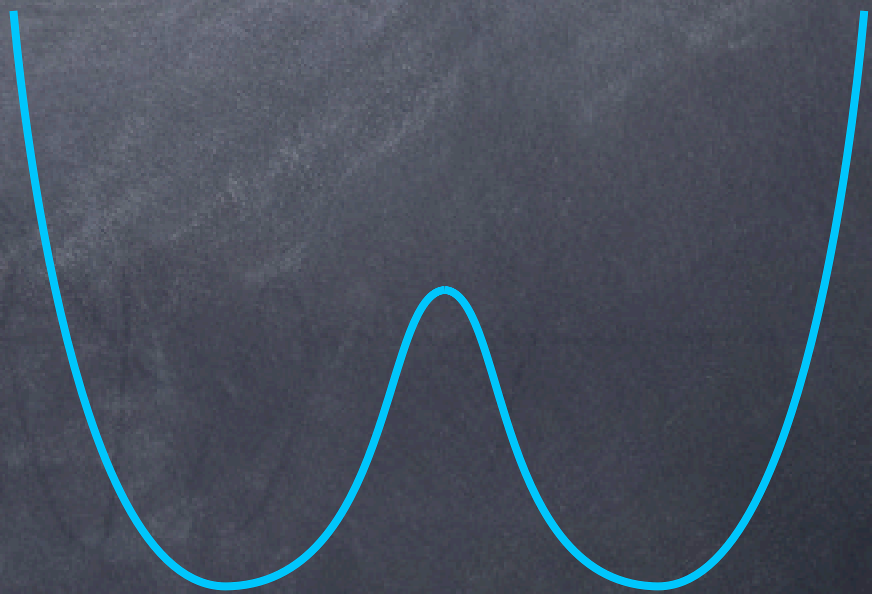
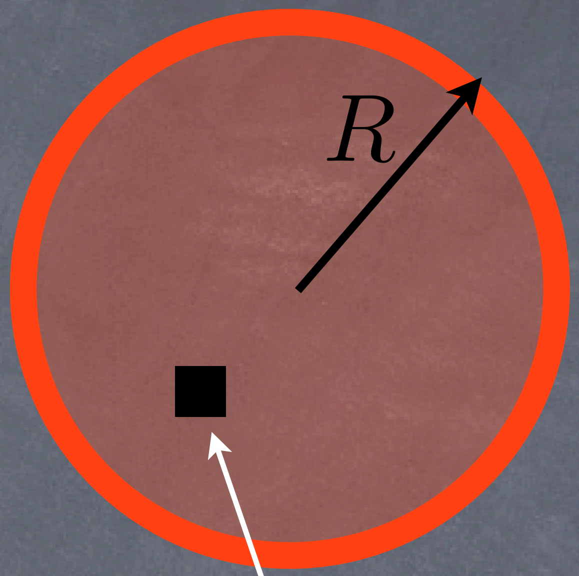
$\sim$



Thin-Shell Screening Effect

Behavior of solution depends on

$$\alpha \equiv \frac{\rho R^2}{M^2} = 6\frac{M_{\rm Pl}^2}{M^2}\Phi_{\rm N}$$



$$\delta\phi \sim \frac{\bar{\phi}}{M^2}\frac{\delta\mathcal{M}}{r}$$

- For sufficiently massive objects, such that $\alpha \gg 1$, solution is suppressed by thin-shell effect:

$$\boxed{\phi_{\rm exterior}(r) \sim \frac{1}{\alpha}\frac{\mathcal{M}}{M_{\rm Pl}^2 r} + \phi_0}$$

- For small objects, $\alpha \ll 1$, we find $\phi \approx \phi_0$ everywhere

$$\Longrightarrow \qquad \phi_{\rm exterior}(r) \sim \frac{\mathcal{M}}{M_{\rm Pl}^2 r} + \phi_0$$

Parameter Constraints

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 + \frac{\phi^2}{2M^2}T^\mu_\mu$$

Necessary (and sufficient) condition is that Milky Way has thin shell:

$$\alpha_{\rm G} = 6\frac{M_{\rm Pl}^2}{M^2}\Phi_{\rm G} \gtrsim 1$$

$$\Phi_{\rm G} \sim 10^{-6}$$

$$\Longrightarrow \quad \boxed{M \lesssim 10^{-3} M_{\rm Pl}}$$

$$\Longrightarrow \quad \mu \sim \frac{M_{\rm Pl}}{M}H_0 \gtrsim {\rm Mpc}^{-1} \qquad \lambda \sim \frac{M_{\rm Pl}^4 H_0^2}{M^6} \gtrsim 10^{-100}$$

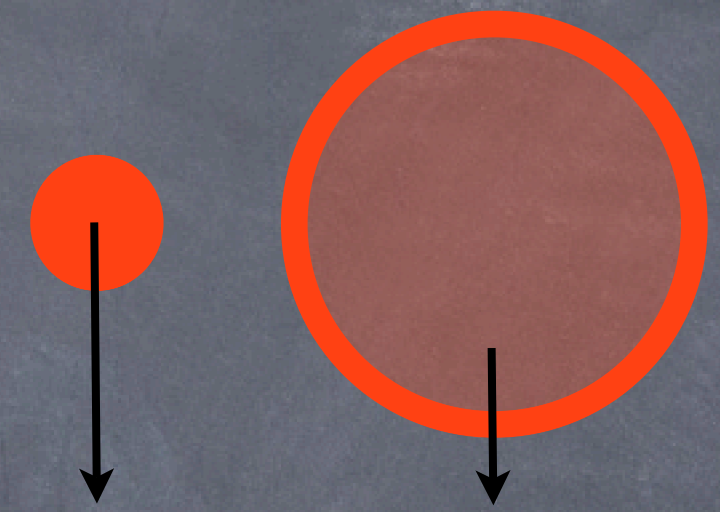
Predictions for Tests of Gravity

Test	Effective parameter	Current bounds
Time delay/light deflection	$\lvert\gamma - 1\rvert \approx 10^{-5}$	$\lvert\gamma - 1\rvert \approx 10^{-5}$
Nordvedt effect	$\lvert\eta_{\rm N}\rvert \sim 10^{-4}$	$\lvert\eta_{\rm N}\rvert \sim 10^{-4}$
Mercury perihelion shift	$\lvert\gamma - 1\rvert \approx 4 \cdot 10^{-4}$	$\lvert\gamma - 1\rvert \approx 10^{-3}$
Binary pulsars	$\omega_{\rm BD}^{\rm eff} \gtrsim 10^{6}$	$\omega_{\rm BD}^{\rm eff} \gtrsim 10^{3}$

Macroscopic Violations of Equivalence Principle

Khoury & Weltman (2003); Hui, Nicolis and Stubbs (2009)

Because of thin-shell screening, macroscopic objects fall with different acceleration in g-field



$$\vec{a} = -\vec{\nabla}\Phi + \epsilon \frac{\phi}{M^2} \vec{\nabla}\phi$$

- Unscreened objects ($\epsilon = 1$) feel gravity + symmetron forces
- Screened objects ($\epsilon = 0$) only feel gravity

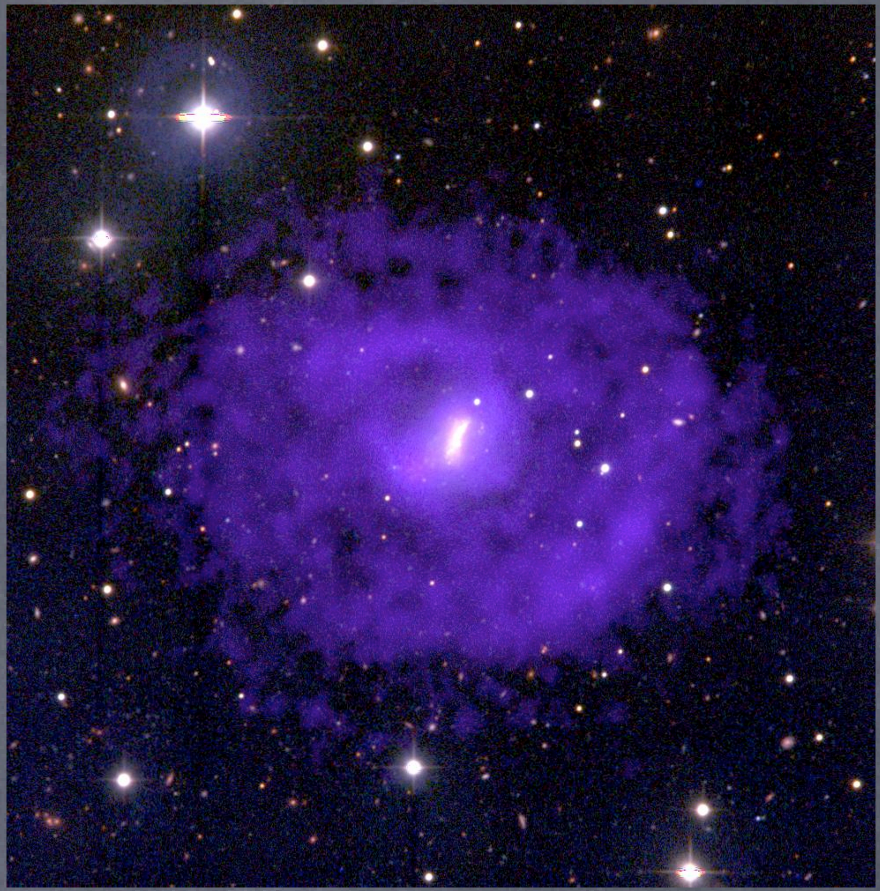
To maximize effect, look for

- large (~ Mpc) void regions, so that symmetry is broken and $\bar{\phi}/M^2 = 1/M_{\rm Pl}$

- look for unscreened objects (i.e. $\Phi < 10^{-7}$) in these voids

Astrophysical signatures

Hui, Nicolis and Stubbs (2009)



- Look at dwarf galaxies in voids

- Stars are screened ($\Phi \sim 10^{-6}$), but hydrogen gas is unscreened. (Gas itself has only $\Phi \sim 10^{-11}$.)

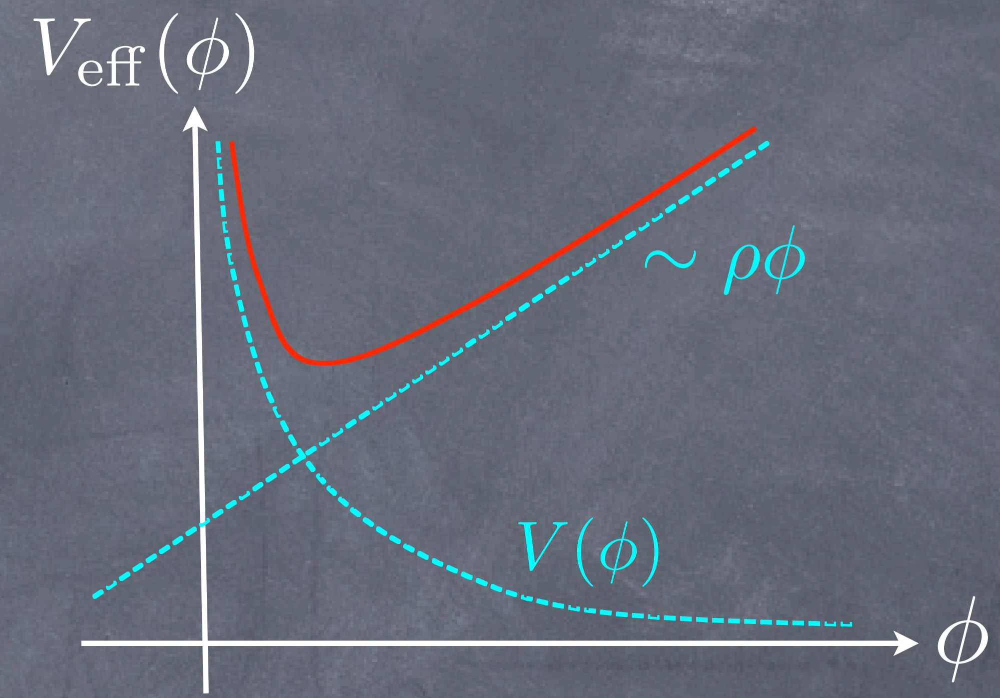
- Should find systematic O(1) discrepancy in the mass estimates based on these two tracers.

NOTE: Effect also possible in chameleon theory but not generic. In the symmetron case, it is generic.

Distinguishable from Other Screening Mechanisms

Chameleon

- Potential is non-renormalizable, e.g. $V(\phi) = M^{4+n}/\phi^n$



- Tightest constraint comes from laboratory tests of gravity, and this results in tiny signals for solar system tests Khoury & Weltman (2003)

Galileon

$$\boxed{3\nabla^2\pi + \frac{1}{\Lambda_{\rm s}^3}\left[(\nabla^2\pi)^2 - (\partial_\mu\partial_\nu\pi)^2\right] = \frac{\rho}{2M_{\rm Pl}}}$$

- Predicts LLR signal measurable by APOLLO, but insignificant time-delay/light deflection signals. Dvali, Gruzinov and Zaldarriaga (2002)

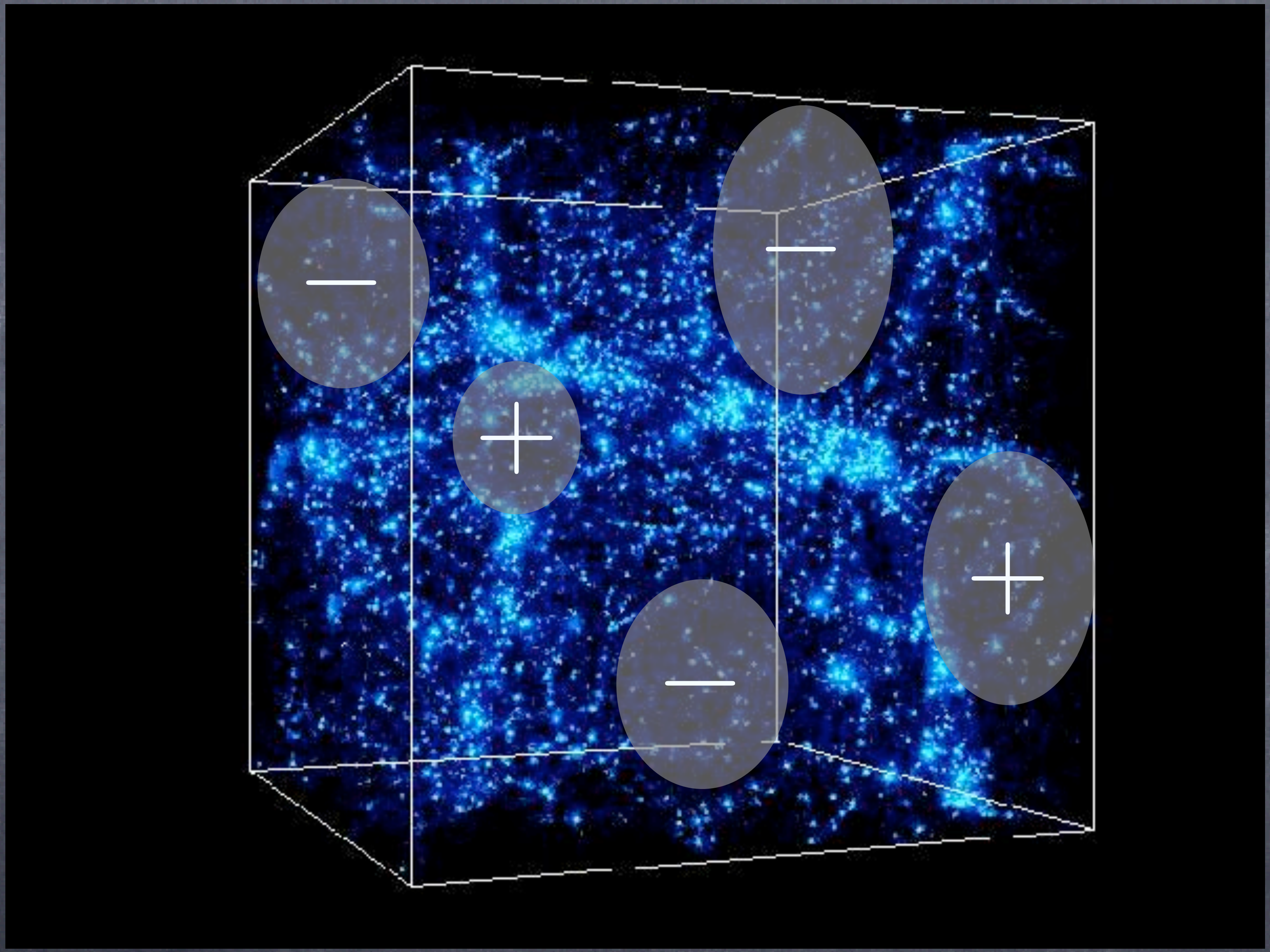
- No macroscopic violations of EP Hui, Nicolis and Stubbs (2009)

In progress...

1. Symmetron Defects

Levy, Matas, Hinterbichler, Hui & Khoury, in progress

In void regions larger than $\mu^{-1} \approx \mathrm{Mpc}$, symmetron takes values $\phi = \pm\mu/\sqrt{\lambda}$

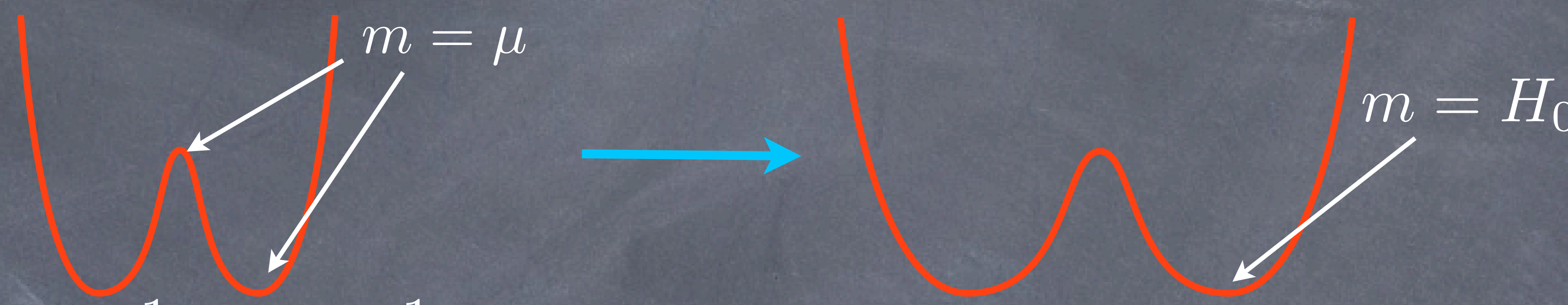


Multiple symmetrons $\Longrightarrow$ global strings, monopoles... ?

2. Cosmology

Levy, Matas, Hinterbichler & Khoury, in progress
Wang, Hui & Khoury, in progress

* Hubble mass:



$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

More general $V(\phi)$

e.g.

$$\boxed{V(\phi) = H_0^2 M_{\rm Pl}^2 \left(e^{-\phi^2/M^2} + \frac{M}{M_{\rm Pl}} e^{\phi^2/M_{\rm Pl}^2} \right)}$$

* Self-acceleration?

$$\tilde{g}_{\mu\nu} = \left(1 + \frac{\phi^2}{2M^2} + \mathcal{O}\left(\frac{\phi^4}{M^4}\right)\right)^2 g_{\mu\nu}$$

If no acceleration in Einstein frame, then can we have acceleration in Jordan frame because $\Delta\phi \sim M$?

3. Tantalizing Hints?

Wyman & J. Khoury, PRD (2010)
Lima, Wyman & J. Khoury, in progress

i) Large Scale Bulk Flows

- Local bulk flow within $50\, h^{-1}\mathrm{Mpc}$ is $407 \pm 81\ \mathrm{km/s}$

Watkins, Feldman & Hudson (2008)

- LCDM prediction is $\approx 180\ \mathrm{km/s}$

Find: $v < 240\ \mathrm{km/s}$

ii) Bullet Cluster (1E0657-57)

- Requires $v_{\mathrm{infall}} \approx 3000\ \mathrm{km/s}$ at 5Mpc separation

Mastropietro & Burkett (2008)

- Probability in LCDM is between 3.3×10^{-11} and 3.6×10^{-9}

Lee & Komatsu (2010)

Find: 10^4 enhancement in prob.

iii) Void phenomenon

Peebles, astro-ph/0712.2757
Nusser, Gubser & Peebles, PRD (2005)

$$V(r) = -\frac{\beta G m^2}{r} e^{-r/r_s}$$

with $\beta \sim \mathcal{O}(1)\ ;\quad r_s \sim \mathrm{Mpc}$

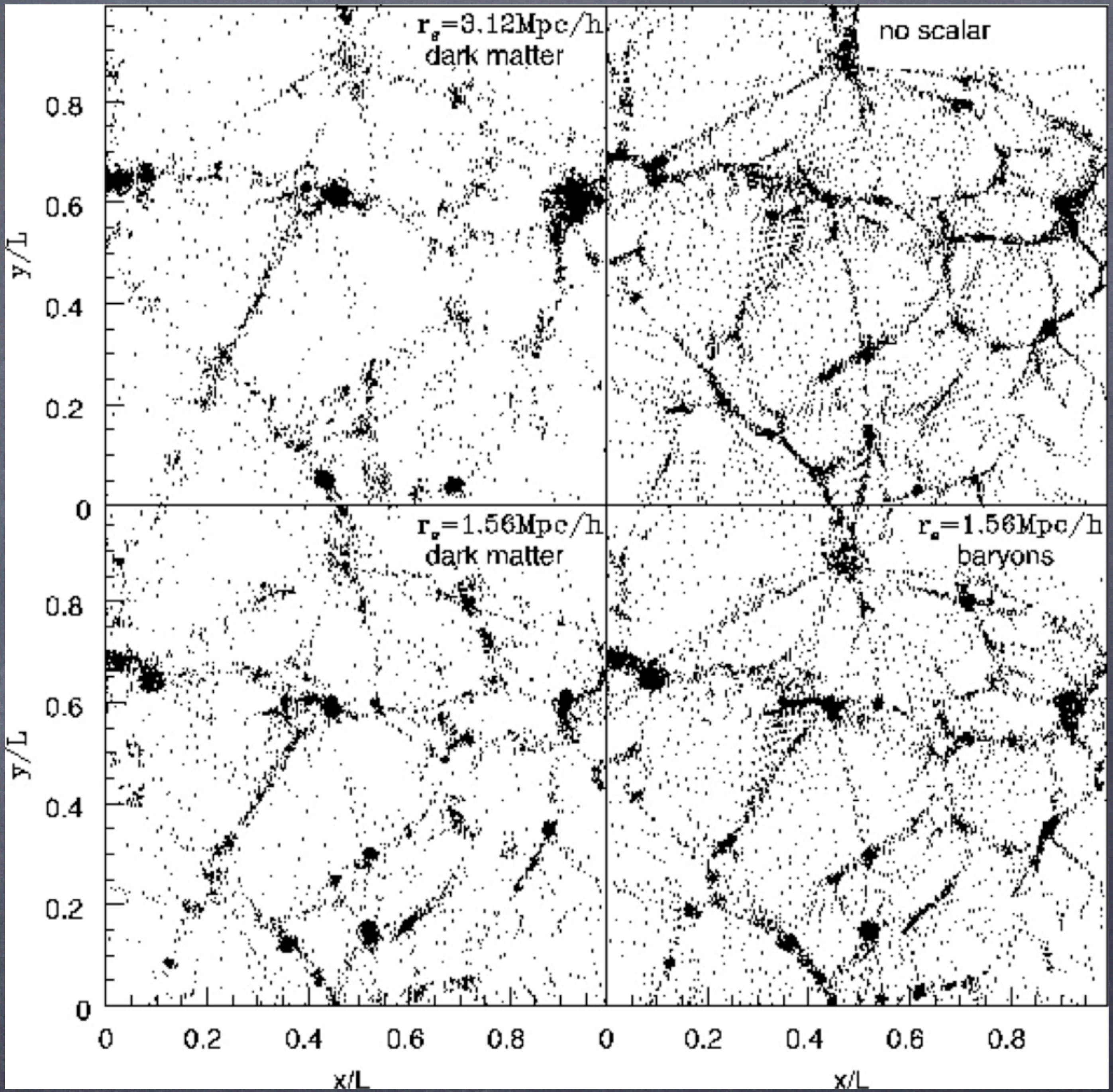
Between DM only!!!

* However, Yukawa force is tightly constrained on galactic scales:

$$\beta < 0.1$$

Kesden & Kamionkowski, PRL (2007)

(See, however, Peebles et al. (2009).)



But screening mechanism circumvents Kesden-Kamionkowski because Milky Way is screened.

Conclusions

- If new forces are associated with dark sector, then some screening mechanism is required by local tests of gravity

- Chameleon and Symmetron mechanisms rely on density-dependent mass and coupling, respectively.

- Rich phenomenology for laboratory, solar-system and cosmological tests of gravity

Cosmological consequences?

- Peculiar velocities, high-velocity mergers, void phenomenon
- Topological defects